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# **SUMS EXPERIMENT FLIGHT RESULTS ON STS-35**

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## Abstract

Calibrated pressure measurements for species with mass to charge ratios up to 50 amu/e<sup>-</sup> were obtained from the Shuttle Upper Atmosphere Mass Spectrometer (SUMS) experiment during reentry on the STS-35 mission. Data were collected from 180 km, when the signal rose above the background, to about 87 km, when the SUMS system automatically closed the gas inlet valve. However, data above 115 km were contaminated from a source of gas emanating from pressure transducers connected in parallel to the mass spectrometer. At lower altitudes, the pressure transducer data are compared to the mass spectrometer total pressure with excellent agreement. The free-stream density in the rarefied flow flight regime is calculated using an orifice pressure coefficient model based upon direct simulation Monte Carlo results. This density, when compared with the 1976 U.S. standard atmosphere model, exhibits the wave-like nature seen on previous flights using accelerometry. In addition, selected spectra are presented at higher altitudes (320 km) showing the effects of the ingestion of gases from a forward fuselage fuel dump. An analysis of the spectra data from this event is presented to show that no significant permanent changes occurred which affected the data interpretation at lower altitudes. Further, the localized chemistry from the individual species during the onset of aerodynamic heating is examined to the extent possible for a closed source system, such as SUMS. Near the orifice entrance, a significant amount of CO<sub>2</sub> was generated from chemical reactions with the carbon panels of the Orbiter and adsorbed oxygen on the system tubing.

## Nomenclature

amu/e <sup>-</sup>	=atomic mass unit per unit charge
(C <sub>p</sub> ) <sub>e</sub>	=equilibrated pressure coefficient
C1,C2	=inlet system flow restrictors (i.e., leaks)
F <sub>i</sub>	=mole fraction of species i
I <sub>i</sub>	=ion current of species i
k <sub>o</sub>	=sensitivity coefficient constant ; 140.0 for range valve closed or 1.0 for range valve open
P <sub>i</sub>	=pressure of species i
P <sub>e</sub>	=equilibrated pressure
P <sub>s</sub>	=surface pressure
P <sub>t</sub>	=total pressure due to all species
q <sub>∞</sub>	=free-stream dynamic pressure (i.e., $\frac{1}{2}\rho V^2$ )
psia	=pounds per square inch absolute
S <sub>i</sub>	=sensitivity coefficient of species i
x,y,z	=body axes
V	=velocity
V1,V2,V3	=inlet valve, dynamic range valve, and protection valve, respectively
α	=angle of attack
β	=sideslip angle
ρ	=density
τ <sub>i</sub>	=change in pressure of species i due to chemistry

## Acronyms

DSMC	=direct simulation Monte Carlo
GSE	=ground support equipment
HiRAP	=High Resolution Accelerometer Package
OEX	=Orbiter Experiments
PCM	=pulse code modulator
SEADS	=Shuttle Air Data System
SIP	=strain isolation pads
STS	=Space Transportation System
TPS	=thermal protection system
UAMS	=Upper Atmosphere Mass Spectrometer

## Introduction

The main objective of the Shuttle Upper Atmosphere Mass Spectrometer (SUMS) experiment is to obtain measurements related to free stream density in the hypersonic, rarefied flow regime during the Shuttle atmospheric reentry.

These measurements, when combined with acceleration measurements, allow the determination of Orbiter aerodynamic coefficients in a flow regime previously inaccessible to experimental techniques. This report presents the results of analysis of flight data from the SUMS experiment taken during the Orbiter's reentry on the STS-35 mission. A complete description of the SUMS experiment is given in Ref. 1; however, a brief review is given here for continuity.

### **Experiment Description**

The main elements of the SUMS flight equipment consist of a 0.1 psia pressure transducer, an inlet system, and a flight mass spectrometer. As depicted in Fig. 1, the pressure transducer is in parallel with the inlet system and it provides backup protection to the mass spectrometer in the event of valve closure failures as well as a source of independent pressure data to compare with the mass spectrometer data. It is important to note that two additional pressure transducers from a different experiment were connected to the same orifice for a total of three transducers connected in parallel with the mass spectrometer.

The inlet system includes stainless steel tubing connecting a filter, an inlet valve, large and small calibrated pinched tube leaks in parallel (see C1 and C2 in Fig. 1), and a dynamic range valve. When the dynamic range valve closes, the gas flows exclusively through leak C2 thereby expanding the measurement range. The mass spectrometer is located remotely from the inlet system within a pressure housing which is filled with sulfur hexafluoride at 1.0 atm pressure. A protection valve is placed in the gas line to the mass spectrometer as a backup to an inlet valve failure. The physical arrangement of the SUMS components on the Orbiter is shown schematically in Fig. 2. Inlet tubing penetrates the Orbiter chin panel just aft of the nose cap and connects to the inlet system after passing through the nose wheel-well bulkhead. The inlet system is connected with another tube to the mass spectrometer which is mounted on the nose wheel-well bulkhead as shown in Fig. 2. The actual installation of the SUMS flight equipment on OV-102 is shown in Fig. 3. The view is looking toward the nose while standing inside the wheel-well. The device on the upper right of the bulkhead is the PCM slave which routes the data to the tape recorder for remote recording on the OEX data system during the Shuttle flight.

The SUMS mass spectrometer is a flight spare from the Viking (Mars Mission) Project Upper Atmosphere Mass Spectrometer (UAMS) experiment that

has been modified to provide mechanical, electrical, and data compatibility with the Shuttle. SUMS experiment operation during flight is controlled by commands stored in the Shuttle computer and by internal "firmware" logic. The application of power for vacuum maintenance and for normal equipment operation is controlled by stored Shuttle commands while internal operation, such as opening and closing valves, is performed by the SUMS control electronics which depend upon atmospheric conditions as measured by the SUMS pressure transducer and/or mass spectrometer.

The mass spectrometer has a mass range of 1 to 50 amu/e<sup>-</sup> in increments of 0.25 amu/e<sup>-</sup> and can measure gases hydrogen (H<sub>2</sub>) through carbon dioxide (CO<sub>2</sub>) at a rate of 1 scan every 5 seconds. One typical 5 second SUMS measurement scan obtained near 90 km altitude during STS-35 is shown in Fig. 4. SUMS is powered on shortly before the initiation of deorbit burn and then samples the inlet gases with the range valve open until an altitude of about 108 km is reached. At that point, the range valve closes leaving only the small leak to transmit gas to the mass spectrometer until about 87 km. Below 87 km, the inlet valve closes, but the mass spectrometer continues to operate until landing to observe the system decay characteristics as it is pumped down. The complete reentry data set on STS-35 consists of approximately 760 scans representing about a 4000 second measurement time interval. The free-stream gas flow relative to the orifice is at an angle of - 29° when the Orbiter is at the nominal reentry angle-of-attack of 40°.

## **SUMS System Calibration**

### **Laboratory Tests**

Calibration of the instrument was accomplished in the laboratory using a setup of specially designed ground support equipment (GSE) connected to the flight hardware. Calibration includes introducing a test gas to the GSE and varying pressure statically (i.e., set a pressure and hold) as well as dynamically (i.e., vary pressure with time). The dynamic test setup provides a method to simulate pressure changes expected during flight. Inlet pressures are then measured (using a sensitive Baretron pressure gauge) and compared to the resulting ion peak currents measured by the mass spectrometer itself. The ion current when divided by inlet pressure provides the sensitivity coefficients (amps/torr) of individual gases (e.g., N<sub>2</sub>, CO, O<sub>2</sub>, and CO<sub>2</sub>) connected to the inlet test setup. This procedure allows the partial inlet pressure of each species to be

determined from a measured ion current in the mass spectrometer during flight. Currents were also recorded for peaks which resulted from the double ionization or "cracking" of a molecule. Examples of these measurements include the ion current peak measured at 14 from doubly ionized  $N_2$  and the ion current peak measured at 28 and 16 as  $CO_2$  splits into  $CO^+$  and  $O^+$ . Knowledge of the doubly ionized to singly ionized ratios and the cracking patterns allows the determination of the amount that each species contributes to a particular peak. This amount is necessary for calculating the correct composition of the gas as it enters the mass spectrometer. These ratios are specific to the SUMS instrument and the important ones are listed in Table 1.

### **System Response Function**

A change in gas pressure at the inlet is not sensed immediately by the mass spectrometer because a time lag response exists due to the enclosed volumes and tube lengths. During some time interval when the descent rate of the Orbiter is fairly constant, the time lag can also be expressed as an altitude shift. Consideration of the shift is most important when SUMS data must be combined with, or compared to other data. For example, to compare the SUMS ambient density predictions to the 1976 U.S. standard atmosphere, it would be necessary to account for the system response time.

An electrical network analog was developed to predict the sensor lag or response function of the SUMS system. The conductances of the inlet tubing and the UAMS terminator were modeled as resistive elements; the volumes of the system were modeled as capacitive elements, and the time dependent input pressure was modeled as an applied voltage. The coefficients of the solutions to the differential equations describing the electrical network model were obtained from a series of static and dynamic calibration laboratory tests of the flight equipment.<sup>2</sup> A volume which represents the tubing forward of the inlet system was used during the tests. However, this laboratory setup did not physically include the two flight pressure transducers which are connected in parallel to the inlet line. Attempts to apply the electrical analog model results for the system as flown were unsuccessful because air, which was trapped behind the filter of each pressure transducer slowly leaked into the system. This effect could not be satisfactorily adapted to the pre-flight system response model results due to the lack of knowledge of the characteristics of the phenomena. Therefore, the electrical analog model proved to be of little practical use for post-flight estimates

of the time lags. However, pressure transducer flight data did allow an experimental determination of the pressure lag for the range valve closed condition.

### **Estimate of the System Response**

#### **SUMS Time Lag**

The SUMS measurement time lag can be determined from the pressure transducer output for the range valve closed condition. The correlation with the pressure measurements requires the calculation of total pressure using the mass spectrometer data. SUMS total pressure can be calculated by summing the individual species measurements as follows:

$$P_t = k_o \sum_i \frac{I_i}{S_i}, \quad (1)$$

where  $k_o$  is a constant dependent upon the state of the range valve;  $I_i$  is the measured ion current of species  $i$ , and  $S_i$  is its sensitivity coefficient. Figure 5(a) shows the results of the calculations from the data taken on STS-35 for the range valve closed condition using species  $N_2$ ,  $O_2$ ,  $CO_2$ ,  $Ar$ , and  $NO$ . Range valve closure occurs at 108 km and the tubing system evacuation process is clearly observed in Fig. 5(a). Included in Fig. 5(a) are the pressure transducer data over the same altitude interval. At these lower altitudes, pressure changes are rapidly transmitted through the tubing, but compositional changes are delayed. It would be expected therefore, that the pressure transducer measurements are nearly instantaneous and that the lag between the mass spectrometer measurements and pressure transducer measurements represents the total lag of the mass spectrometer system. An apparent 0.2 km lag (1.5 seconds) is seen in Fig. 5(a) at the lower altitudes. Figure 5(b) shows the improved results, particularly below 95 km, after a 0.2 km upward altitude shift is applied to the SUMS data. This shift is based on the measured total pressure referenced to the start of the scan time. The individual ion currents have been interpolated to this common time.

#### **Leak Switch Transient**

The comparison between the pressure data and the mass spectrometer data at altitudes beyond the data transmission gap (above 97 km) does not compare well in Fig. 5(b). The main difference is due to the remnants of gas trapped in the



tubing after the leak switch. Removing this transient requires an application of the pump-down characteristics of the system.

After the range valve closes, gas remains in the tubing and requires some time before it is pumped from the system. SUMS measures this gas in addition to the fresh gas which is sampled from the atmosphere. As a result, the data obtained after the range valve closes contains a decaying pressure transient as shown in Fig. 6 for the Nitrogen component. This transient pressure drop can be estimated by observing the system pump down characteristics after the inlet valve closes and no more external gas enters the system. By subtracting the percent drop per measurement time interval in the pump down region, the transient can be removed from each of the species and a corrected data set can be obtained. This correction can be applied to the data shown in Fig. 5(b) to obtain an improved measurement, particularly for altitudes above 95 km. When this effect is removed, excellent agreement is noted with the pressure transducer data as shown in Fig. 7.

## **Free Stream Density Determination**

### **Equilibrated Pressure Coefficient**

In flight, the total surface pressure measured at the SUMS inlet tube is higher than the free stream dynamic pressure.<sup>3,4</sup> Inside the tube, the gas pressure quickly drops as it equilibrates to the wall temperature of the inlet tube. To obtain information about the ambient atmospheric conditions from the SUMS instrument, it is necessary to determine the relationship between the free stream pressure and the inlet tube equilibrated pressure which is subsequently measured by the mass spectrometer. The approach involves a model of the flow field and a model of the gas behavior in the tube near the entrance of the inlet orifice.<sup>5</sup> Results from a theoretical model using direct simulation Monte Carlo (DSMC) calculations were developed specifically for the SUMS instrument<sup>6</sup> so that the equilibrated pressure,  $P_e$ , could be related to the free stream dynamic pressure,  $\frac{1}{2}\rho V^2$ , by the equilibrated pressure coefficient,  $(C_p)_e$ , which is defined as:

$$(C_p)_e = \frac{P_e}{\frac{1}{2}\rho V^2} = \frac{P_e}{q_\infty} \quad (2)$$

The  $(C_p)_e$  values used in this analysis are shown as a function of  $P_e$  in Fig. 8.

Shown on the figure are the data from Ref. 6 along with a curve which is derived from a combination of pressure and accelerometer flight data. The higher altitude  $(C_p)_e$  data developed for the SUMS instrument did not extend to the lowest measurement altitudes. For this reason, an experimental pressure coefficient was developed based on pressures measured by the pressure transducers, accelerations measured by the HiRAP accelerometer, and aerodynamic coefficients inferred from previous HiRAP flights.<sup>7</sup> The experimental pressure coefficient is the product of a flow-field coefficient ratio which relates the surface pressure to the free-stream dynamic pressure and an inlet coefficient ratio which relates the equilibrated internal pressure to the surface pressure. That is,

$$(C_p)_e = \frac{P_s}{q_\infty} \frac{P_e}{P_s} \quad (3)$$

As continuum conditions are approached during reentry, the flow-field coefficient ratio decreases while the inlet coefficient ratio rapidly increases. Results of a 7th order curve fit to the flight data are shown for  $(C_p)_e$  on Fig. 8. This curve is used for pressures greater than about 10 N/m<sup>2</sup>. At lower pressures, a curve fit (not shown) to the Moss and Bird<sup>6</sup> data is used. In this figure the coefficient increases steadily with pressure until reaching a value of about 1.5 where it levels and gradually declines to about 1.41, the modified Newtonian limit. The experimental pressure coefficient extends the DSMC analytic model to higher pressures, but for pressures above 100 N/m<sup>2</sup>, the experimental coefficient exceeds the theoretical limit of 1.41 which is calculated using the modified Newtonian approach for continuum hypersonic conditions. An explanation for this result is that when using any common criteria for continuum conditions, such as the ratio of molecular mean-free-path to characteristic length, the inlet coefficient reaches a continuum state before the flow-field coefficient.

A rearrangement of Eq. (2) can be applied to the SUMS equilibrated pressure measurements to allow the calculation of the dynamic pressure and, subsequently, the free stream density. That is, given  $P_e$  as measured by the SUMS (or a pressure transducer), and the  $(C_p)_e$  model (Fig. 8), the dynamic pressure is simply the ratio of these quantities. With dynamic pressure, the atmospheric

density,  $\rho$  can be calculated since velocity,  $V$ , is known from the trajectory reconstruction process.<sup>8</sup>

### **Density Results**

SUMS data were gathered from orbital altitudes (~346 km) down to approximately 87 km where the inlet valve closed. Fig. 9 shows the altitude profile as flown during a portion of the STS-35 reentry mission. SUMS spectra scans are transmitted continuously from deorbit altitude, but, for this flight, the SUMS signal came out of the background at about 180 km (labeled "Measurable Signal"). The delay in the signal emerging from the background signal was unexpected and later investigations identified the cause to be trapped gas behind the filters of the pressure transducers. The details of the background signal will be discussed later. Thus, during reentry, SUMS data covered an interval of about 18 minutes from approximately 180 km to 87 km. During this time interval, the Orbiter was at an angle-of-attack of about  $40^\circ$  traveling at a speed of about 7500 m/s. Figure 9 also shows the altitude location of the range valve closure which switches leaks (labeled "Range Valve Closed") and allows measurements deeper into the atmosphere.

The density has been calculated from the mass spectrometer spectra using the method outlined in the previous section, and is shown in Fig. 10. Included in the figure, for comparison, is the density from the 1976 U.S. standard atmosphere model.<sup>9</sup> At altitudes less than 115 km, the SUMS data compare well with the model and show traces of the characteristic wavy density pattern that appear in other separate flight experimentation.<sup>10</sup> At higher altitudes ( $> 115$  km), however, the data obviously are being influenced by the background gas.

### **System Background**

The background levels of the spectra taken at orbital altitudes were extraordinarily high. An extensive investigation of the equipment after the flight revealed that ground composition air was trapped behind the filter within each pressure transducer connected in parallel to the mass spectrometer. Most of the trapped air escaped quickly as the Shuttle attained orbit. However, once in orbit, the pressure dropped, and free molecule flow conditions were reached causing the effective conductivity of the filters to drop to only a fraction of that at higher pressures. Under these conditions, the remaining air leaked continuously into

the inlet tubing producing a small background pressure source while on orbit. The pressure was nearly constant at about  $.08 \text{ N/m}^2$ , and the composition ( $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{Ar}$ , and  $\text{CO}_2$ ) matched sea level air.

Figure 10 shows the effect of the trapped air background source on the density calculations. Above about 120 km, an exponential-like free-stream density decrease is expected, but the density is unreasonably high at a near constant level. Indeed, the density measurements eventually exceed a standard atmosphere by a factor of more than 10. A similar unreasonable density result occurs when the measurements are corrected by simply subtracting a constant background. Only by subtracting a semi-empirical variable background pressure can a reasonable behavior of density variation be obtained. Based on these results, it is concluded that the background pressure during the high altitude measurements varies in a manner which requires further study of the conductances of the pressure filters before a reliable background model can be established. For this reason, the high altitude data are not reliable. Below about 120 km, the external pressure of the gas rises high enough so that the background source is no longer a contributing factor and reliable results can be obtained.

### Fuel Dump Analysis

During a period of about 120 seconds, as the Orbiter descended through 320 km, pulses were observed in the SUMS spectra data for some of the species. Upon a closer examination of the HiRAP<sup>6</sup> accelerometer data on STS-35, it was clear that the spectra were affected by the ingestion of gas from the forward fuselage fuel dump of methyl-hydrazine ( $\text{CH}_3\text{HN}_2\text{H}_2$ ). Figure 11(a) shows the Orbiter x body axis accelerometer data taken during reentry. At about 18,300 seconds GMT, the HiRAP sensor detected a large (600 ug) x-axis disturbance which was traced to the forward fuselage fuel dump prior to the entry interface. An examination of the spectra data was made in order to determine if the fuel gas contaminants altered the interpretation of the data at lower altitudes. Figure 11(b) shows the corresponding ion currents measured by SUMS for some selected species during the fuel dump time period. Most noticeable is the large peak at  $15 \text{ amu/e}^-$  which is assumed to be the methyl radical,  $\text{CH}_3$ . Both the methyl-hydrazine at  $46 \text{ amu/e}^-$  and  $\text{HN}_2\text{H}_2$  (i.e., a free radical resulting from  $\text{CH}_3$  splitting from methyl-hydrazine) at  $31 \text{ amu/e}^-$  show no appreciable increases and

are not shown in Fig. 11(b). Similarly, both the water at 18 amu/e<sup>-</sup> and the OH at 17 amu/e<sup>-</sup> show no peak.

The remaining species (N<sub>2</sub>, O<sub>2</sub>, CO<sub>2</sub>, Ar, and O) all show increases in varying amounts. Nitrogen (28 amu/e<sup>-</sup>) shows a peak which could possibly be due to a decomposition product of methyl-hydrazine, or could be swept from the system walls. Ion peaks appear at both 32 and 16, but the 16 peak relative to its pre-dump background readings is much larger than the 32 peak compared to its background. If we examine the ratio  $I_{16}/I_{32}$ , shown on Fig. 12(a), then this difference becomes evident. Since the ratio persists at a level larger than the pre-dump background and seems to decay toward it, this result suggests that CH<sub>4</sub> has been generated and is adhering to the walls. Below about 180 km, the ratio decreases abruptly as the O<sub>2</sub> concentration increases.

The 16 ion peak can be predicted using the ionization and cracking ratios in Table 1, assuming that the 16 ion peak was produced totally from O<sub>2</sub> (32) and CO<sub>2</sub> (44). When  $I_{16}$  observed is divided by  $I_{16}$  predicted using this assumption, a huge peak appears at the time of the dump as seen in Fig. 12(b). The fact that this ratio is much larger than unity demonstrates that the 16 peak is not coming solely from O<sub>2</sub> and CO<sub>2</sub>.

Figure 13 shows the ratio of  $I_{14}$  measured to  $I_{14}$  predicted, assuming  $I_{14}$  predicted comes from doubly ionized N<sub>2</sub> and from doubly ionized CO, which comes from CO<sub>2</sub>. The ratio is near unity throughout except for a small drop at the time of the fuel dump, as can be seen in Fig. 13. This suggests that CO rises in the system slightly after the fuel dump over that produced from CO<sub>2</sub> fractionation, but is pumped from the system readily.

Based upon the preceding analysis, the spectra after the fuel dump showed no significant permanent changes occurred due to the ingestion of the fuel gas into the system.

### Chemistry Considerations

It is well known<sup>11</sup> that high temperature flow phenomena at lower altitudes cause chemical reactions which change the local undisturbed atmospheric composition. Thus, it is expected that the composition measured by SUMS differs from the composition near the orifice entrance, and is different from the ambient atmosphere. It is possible to gain some insights into the behavior of the gas composition near the Orbiter surface at the onset of aerodynamic heating. Mass

spectrometer species data provide more information than a simple pressure transducer, but the information is not complete since the behavior of atomic oxygen (and other highly reactive species) is totally masked by a closed source system, such as SUMS.

The mole fraction,  $F_i$ , for species  $i$  in a gas mixture containing  $n$  species can be calculated using the equation,

$$F_i = \sum_j \frac{P_i}{P_j} , \quad j=1, 2, \dots, n \quad (4)$$

where  $P_i$  is the partial pressure of species  $i$  and the  $P_j$ 's are the partial pressures of the  $n$  gases measured by the mass spectrometer. The mole fractions for  $\text{CO}_2$ ,  $\text{O}_2$ , and  $\text{N}_2$  are shown as a function of altitude in Figure 14(a). Together with Ar, which remains constant at approximately 1 percent, the partial pressures of these species combine to account for almost all of the pressure measured by the mass spectrometer on STS-35. For reference, Fig. 14(b) is a graph of the mole fractions of the ambient atmosphere based upon the 1976 U.S. standard atmosphere model.<sup>9</sup> For these calculations, atomic oxygen is combined with  $\text{O}_2$  to represent the total number of oxygen molecules available to the mass spectrometer before flow-field chemistry. That is, all of the atomic oxygen which does not react with other elements, or is not adsorbed by the walls, combines to form  $\text{O}_2$  before it is measured by the mass spectrometer. As seen in Fig. 14(a), the mole fractions remain fairly constant to about 100 km, similar to expectations without flow-field chemistry. It is not until below about 100 km that the mole fractions begin to change. At that altitude, both the  $\text{O}_2$  and  $\text{N}_2$  mole fractions begin to decrease as the mole fraction of  $\text{CO}_2$  begins to increase. Since  $\text{CO}_2$  concentration rapidly increases, chemistry caused by aerodynamic heating has begun.<sup>12</sup> There are at least two sources of carbon; one is the carbon in the steel tubing, and the other is the Orbiter's surface chin panel and nose cap which are made of coated carbon-carbon materials. The exact method for the production of  $\text{CO}_2$  is not known, but a possible mechanism is that the heated carbon-carbon chin panels near the Orbiter's nose region interact with oxygen to produce a mixture of C, CO, and  $\text{CO}_2$ . This mixture then reacts with atomic oxygen adsorbed to the walls of the inlet tubing, and produces almost exclusively  $\text{CO}_2$  before being measured by the mass spectrometer.

The change in partial pressure of species  $i$ ,  $\tau_i$ , due to chemistry sources or sinks can be estimated using the above equation by letting

$$P'_i = P_i + \tau_i, \quad (5)$$

where  $P_i$  is the partial pressure of species  $i$  if there were no aerodynamic heating and  $P'_i$  is the altered partial pressure of species  $i$  due to aerodynamic heating ( $P'_i$  is measured by the mass spectrometer). The values of  $\tau_i$  can be solved by combining Eq. (5) with Eq. (4) and considering the mole fractions prior to aerodynamic heating as constants i.e., similar to Fig. 14(b). Assuming that  $N_2$  undergoes no chemical changes due to heating results in 4 independent equations and 4 unknowns for a gas consisting of  $CO_2$ ,  $O_2$ , and  $N_2$ . The 4 unknowns are the pressures  $P_{CO_2}$  and  $P_{O_2}$  (both without chemistry changes), and the pressure changes  $\tau_{CO_2}$ , and  $\tau_{O_2}$  at any altitude. The results from the solution of these equations, as a function of altitude, are shown in Fig. 15. The results, expressed as a percentage, show that the production of  $CO_2$  is significant; over 20 percent of the gas measured at lower altitudes is  $CO_2$ . Concurrently, at this altitude, oxygen is being depleted by about 7 percent of the total gas sampled, which represents nearly half of the oxygen measured.

It is worth reiterating that the actual chemical composition at the orifice entrance is probably different due to the presence of atomic oxygen. At altitudes near 100 km, the standard atmosphere model predicts an ambient composition containing about 10 percent atomic oxygen,  $O$ . Any molecular oxygen,  $O_2$ , dissociation in the shock/boundary layer would produce additional atomic oxygen, but as expected, atomic oxygen was not measured at any altitude during the SUMS experiment. This result suggests that  $O$  readily combined with carbon and other molecules before it was measured.

## Conclusions

The SUMS experiment has provided partial pressure measurements in the altitude range from 180 km to 87 km during STS-35 reentry. However, above about 115 km altitude, the measurements are contaminated with sea level composition air. The source of this contamination was identified as a slow release of gas trapped behind pressure transducer filters which were connected in parallel to

the mass spectrometer. Below about 115 km, as the Orbiter surface pressure rises to values much larger than the trapped gas source, the sum of the SUMS partial pressure measurements correlate well with available local pressure transducer measurements. The free-stream density in the rarefied-flow regime has also been calculated from the SUMS measurements. The procedure involved using an analytical/empirical model for the pressure coefficient at the SUMS orifice. The SUMS density measurements corroborate earlier accelerometer measurements which indicate that large scale density waves exist in the upper atmosphere relative to standard atmosphere models. At 320 km, the SUMS registered the effects of the gas resulting from the Orbiter forward fuselage fuel dump. Examination of the spectra in this altitude region showed a large 15 ion current peak transient, probably  $\text{CH}_3$ , along with other species, but no significant permanent changes occurred due to the ingestion of the fuel gas into the system. The initial effects on gas composition due to aerodynamic heating were observed beginning at about 100 km. The production of  $\text{CO}_2$  and the corresponding depletion of  $\text{O}_2$  are clearly seen as the reactive gases from the flowfield, near the surface, react with the abundant carbon from the carbon-carbon nose and chin panels and subsequently with some of the atomic oxygen adhering to the tubing walls. It is estimated that at the lowest measurement altitude of SUMS (87 km), about 20% of the total pressure comes from  $\text{CO}_2$ .

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<sup>8</sup>Oakes, K. F., Findlay, J. T., Jasinski, R. A., and Wood, J. S., "Final STS-35 'Columbia' Descent BET Products and Results for LaRC OEX Investigations," NASA CR-189569, Nov. 1991.

<sup>9</sup>U.S. Standard Atmosphere, 1976, NOAA, NASA, USAF, Oct. 1976.

<sup>10</sup>Blanchard, R. C., Hinson, E. W., and Nicholson, J. Y., "Shuttle High Resolution Acceleration Package Experiment Results: Atmospheric Density Measurements Between 60-160 km," Journal of Spacecraft and Rockets, Vol. 26, No. 3, May-June 1989, pp. 173-180.

<sup>11</sup>Cuda, V. Jr., Moss, J. N., "Direct Simulation of Hypersonic Flows Over Blunt Slender Bodies," AIAA Paper No. 86-1348, June 1986.

<sup>12</sup>Hartung, L.C., and Throckmorton, D. A.: "Space Shuttle Entry Heating Data Book, Volume 1-STS-2, Parts 1 and 2," NASA RP-1191, May 1988.

**Table 1.** SUMS Ionization and Cracking Ratios for CO, N<sub>2</sub>, O<sub>2</sub>, Ar, and CO<sub>2</sub>

<u>GAS</u>	<u>MASS (amu)</u>	<u>ION CURRENT RATIOS</u>	
<i>Carbon monoxide, CO</i>	28	$I_{12}/I_{28}$	.024
		$I_{14}/I_{28}$	.012
		$I_{16}/I_{28}$	.0056
<i>Nitrogen, N<sub>2</sub></i>	28	$I_{14}/I_{28}$	.068
<i>Oxygen, O<sub>2</sub></i>	32	$I_{16}/I_{32}$	.075
<i>Argon, Ar</i>	40	$I_{20}/I_{40}$	.27
<i>Carbon Dioxide, CO<sub>2</sub></i>	44	$I_{14}/I_{44}$	.0007
		$I_{16}/I_{44}$	.12
		$I_{22}/I_{44}$	.033
		$I_{28}/I_{44}$	.06

**Not to scale**

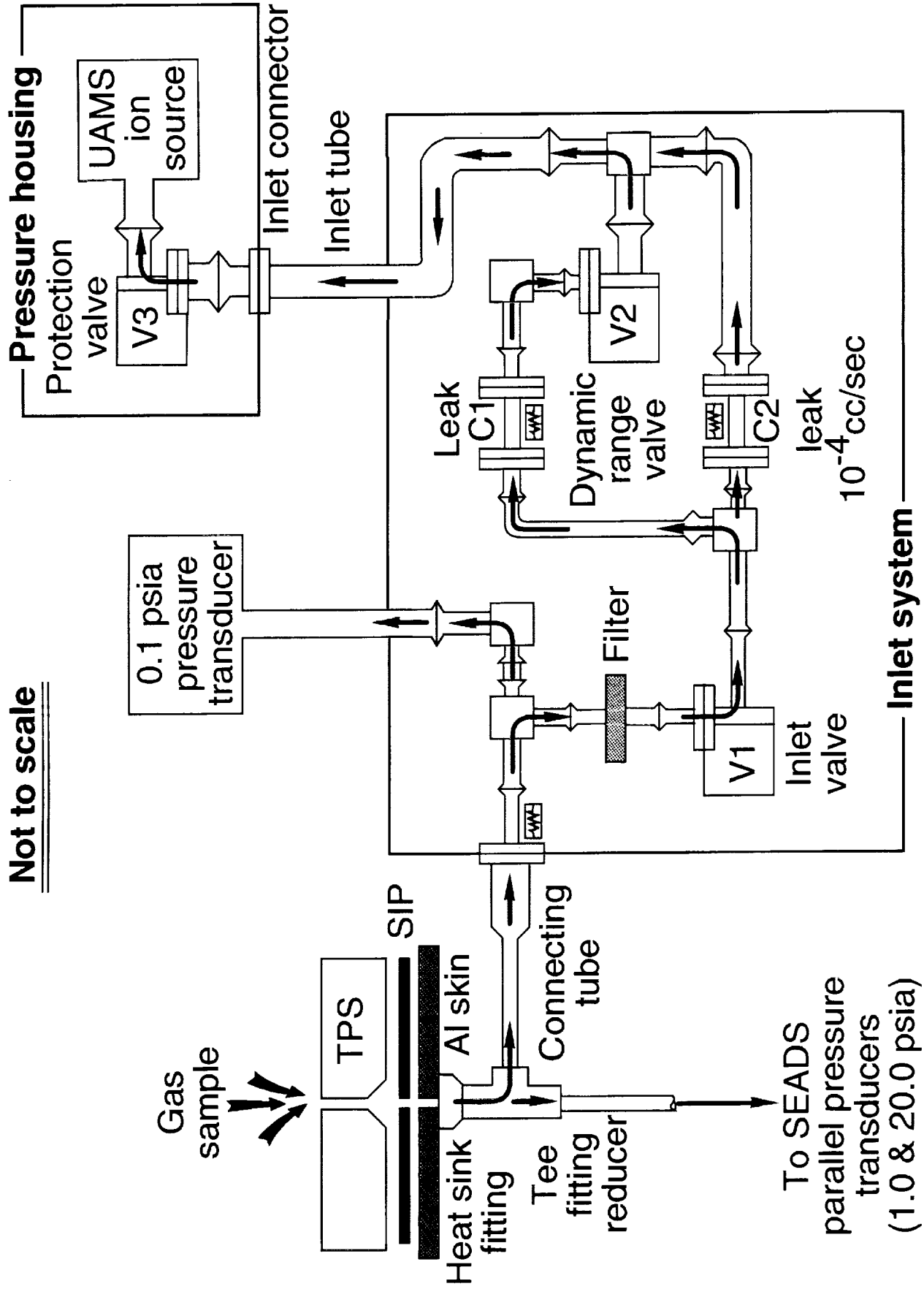


Fig. 1 SUMS system planar flow diagram.



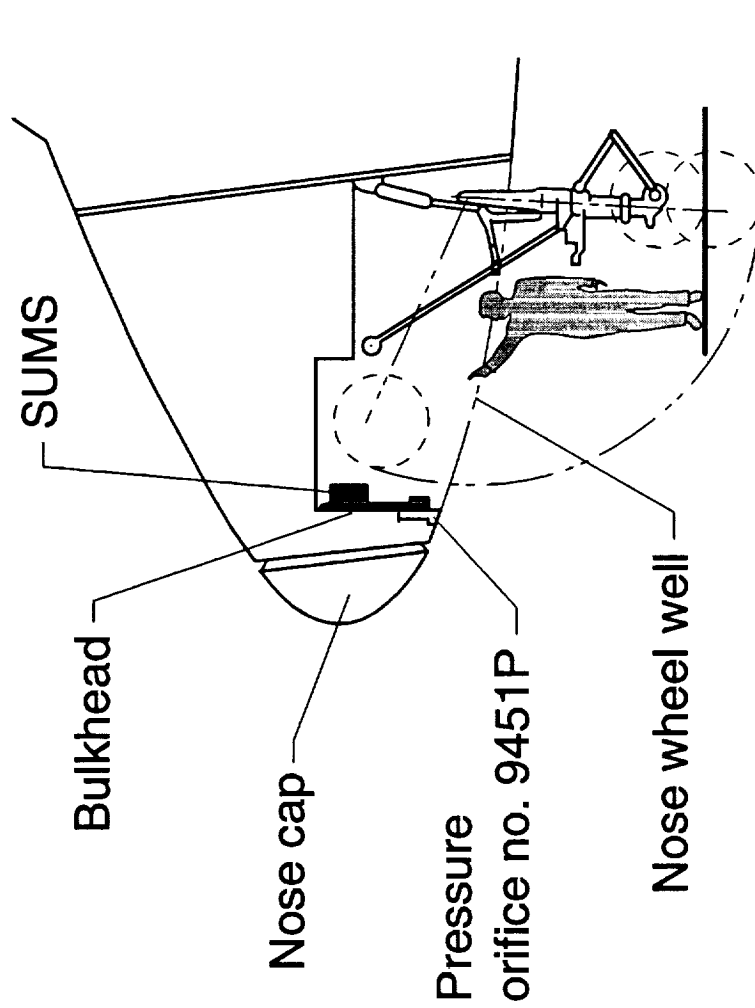


Fig. 2. SUMS instrument location in the Shuttle nose wheel well.



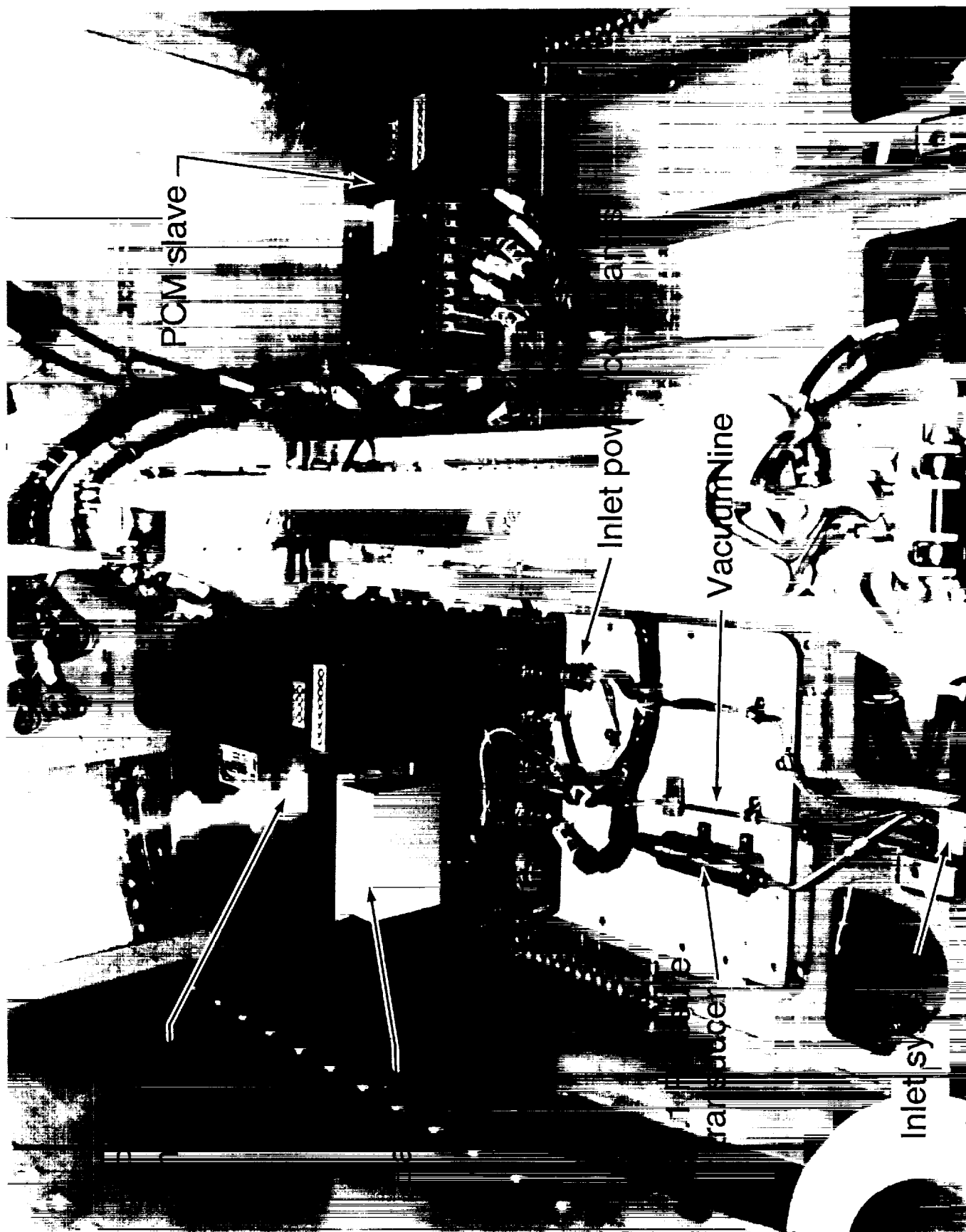


Fig. 3 SUMS installed in STS-35 wheel well.





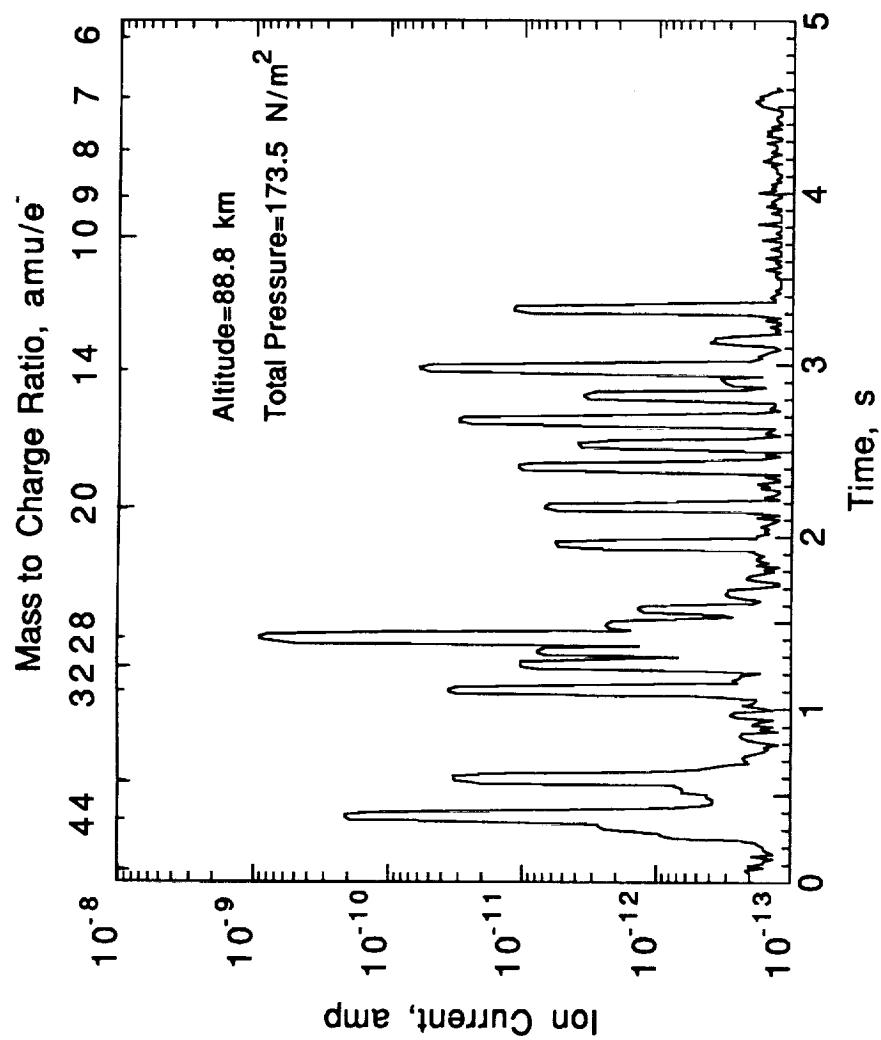


Fig. 4. Typical SUMS spectra taken on STS-35.



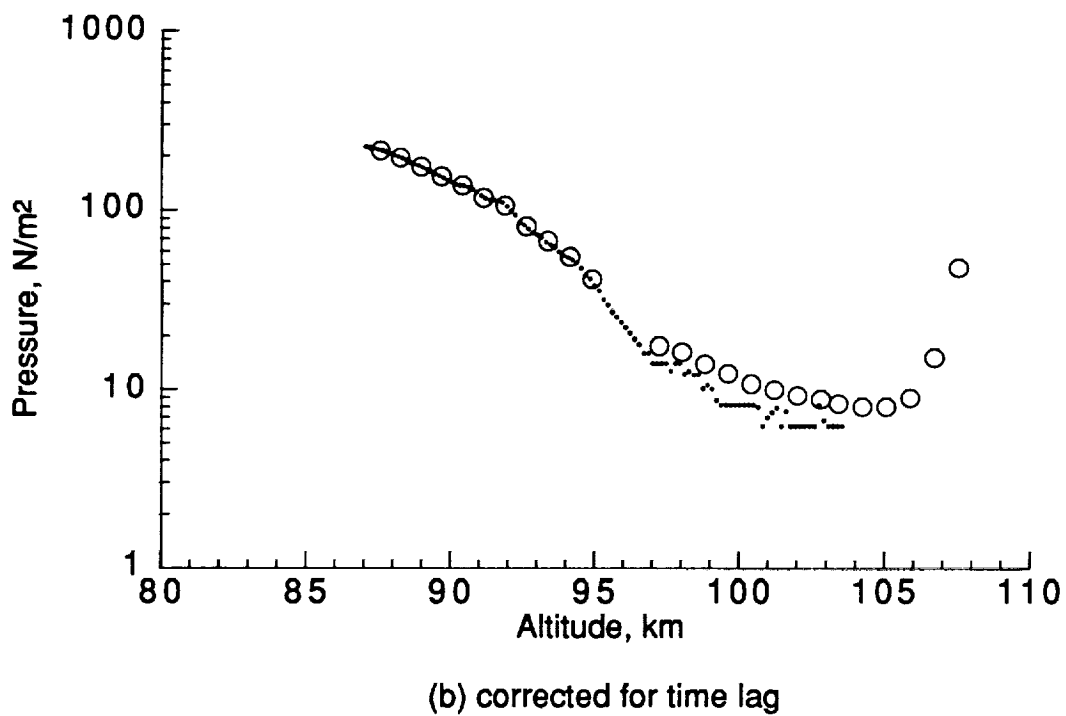
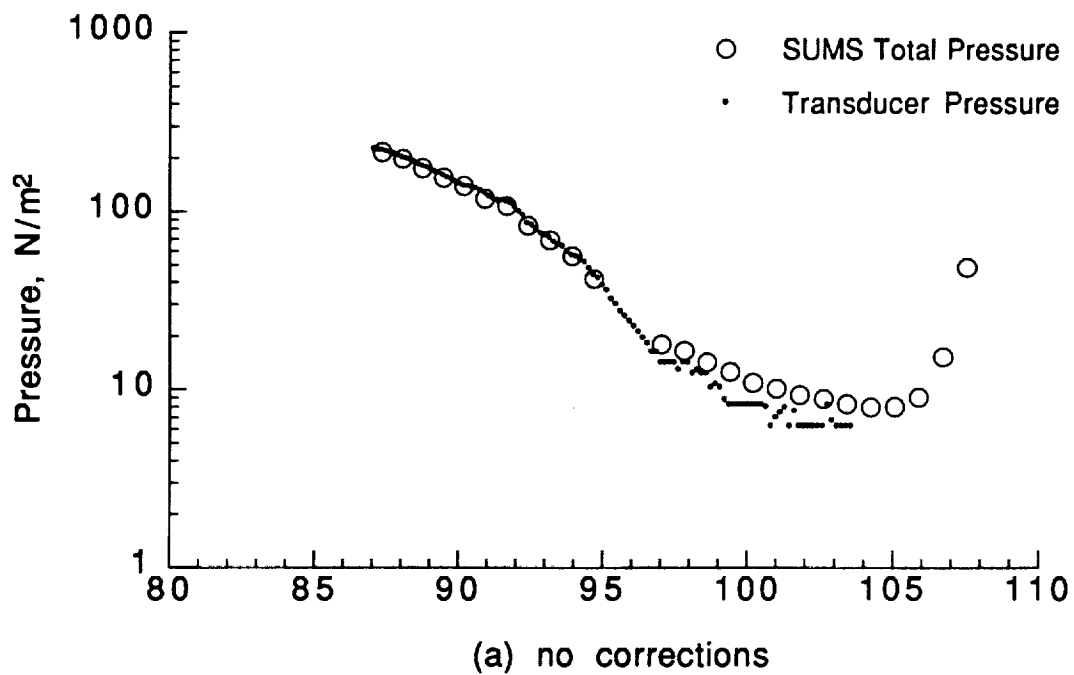


Fig. 5. SUMS total pressure and transducer measurements

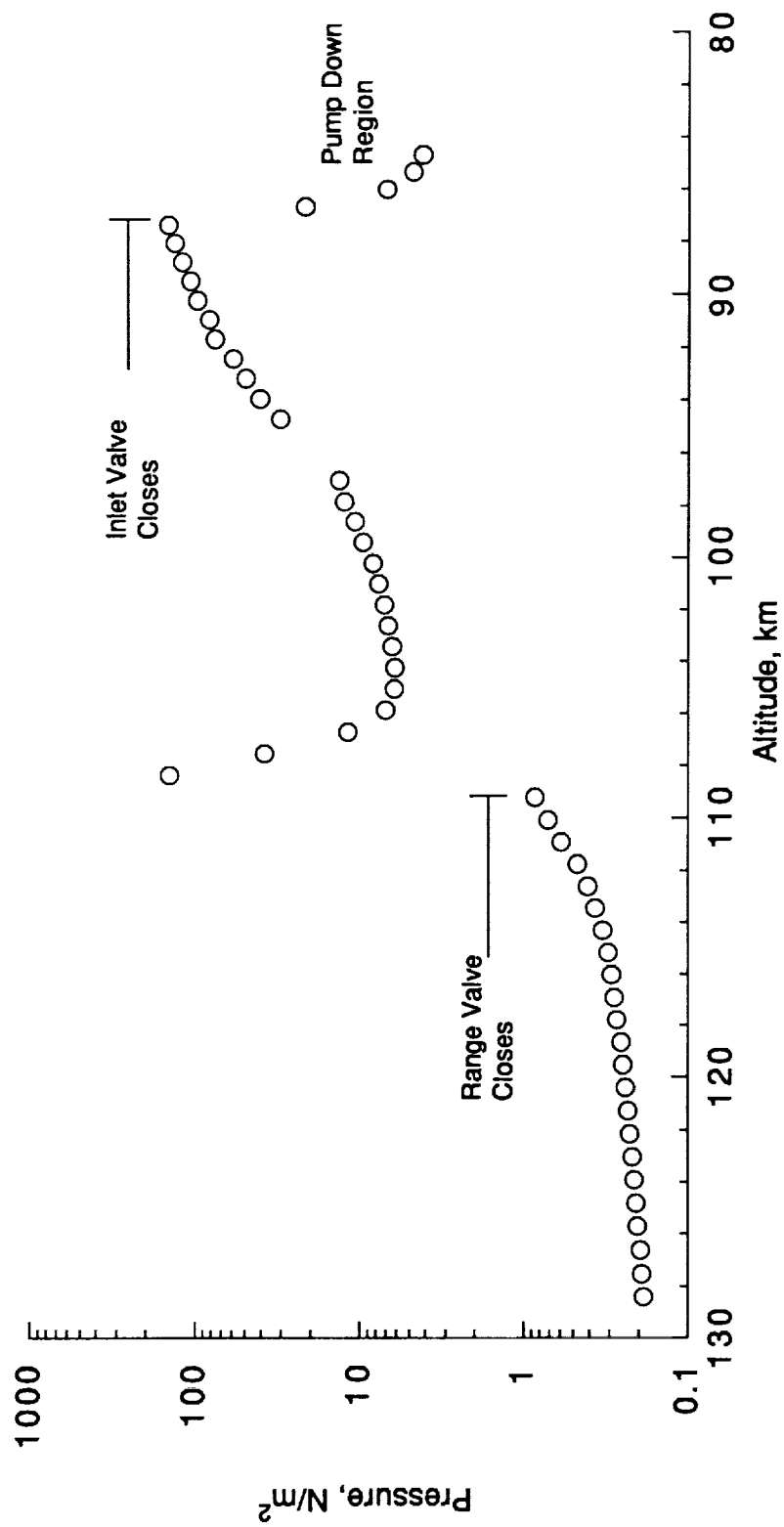


Fig. 6. SUMS Nitrogen pressure measurements

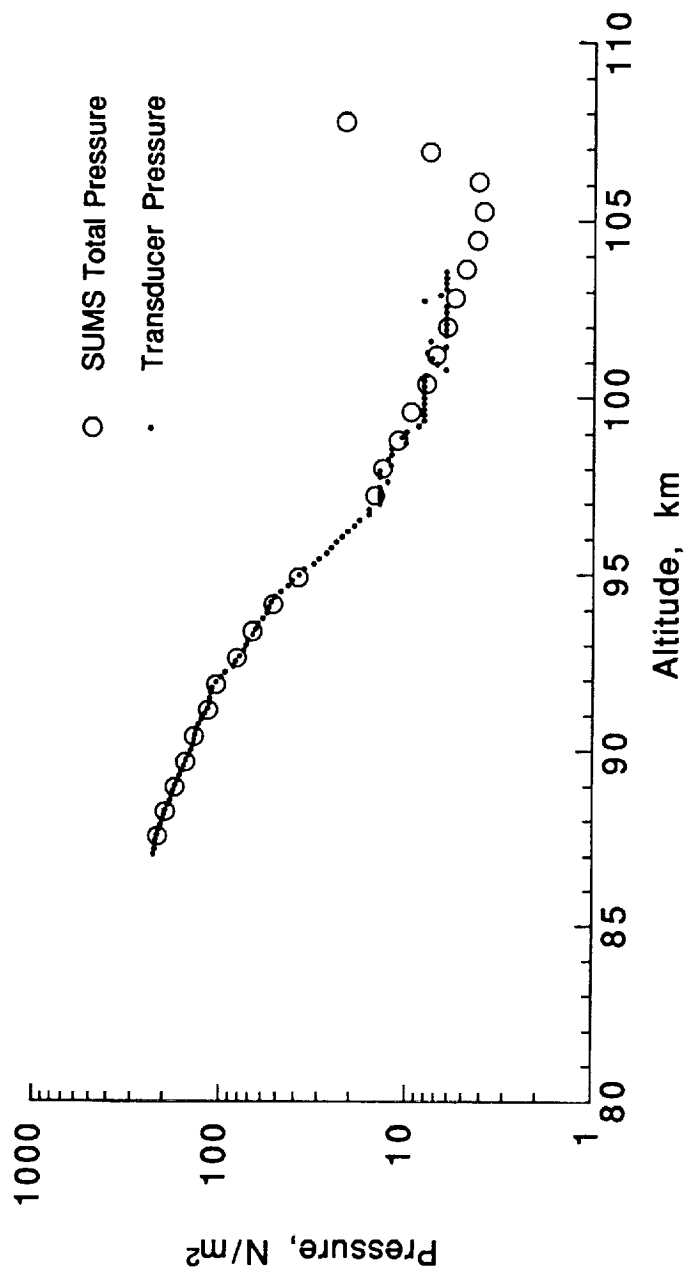


Fig. 7. Comparison of transducer data with SUMS total pressure measurements corrected for valve closure transient and time lag.

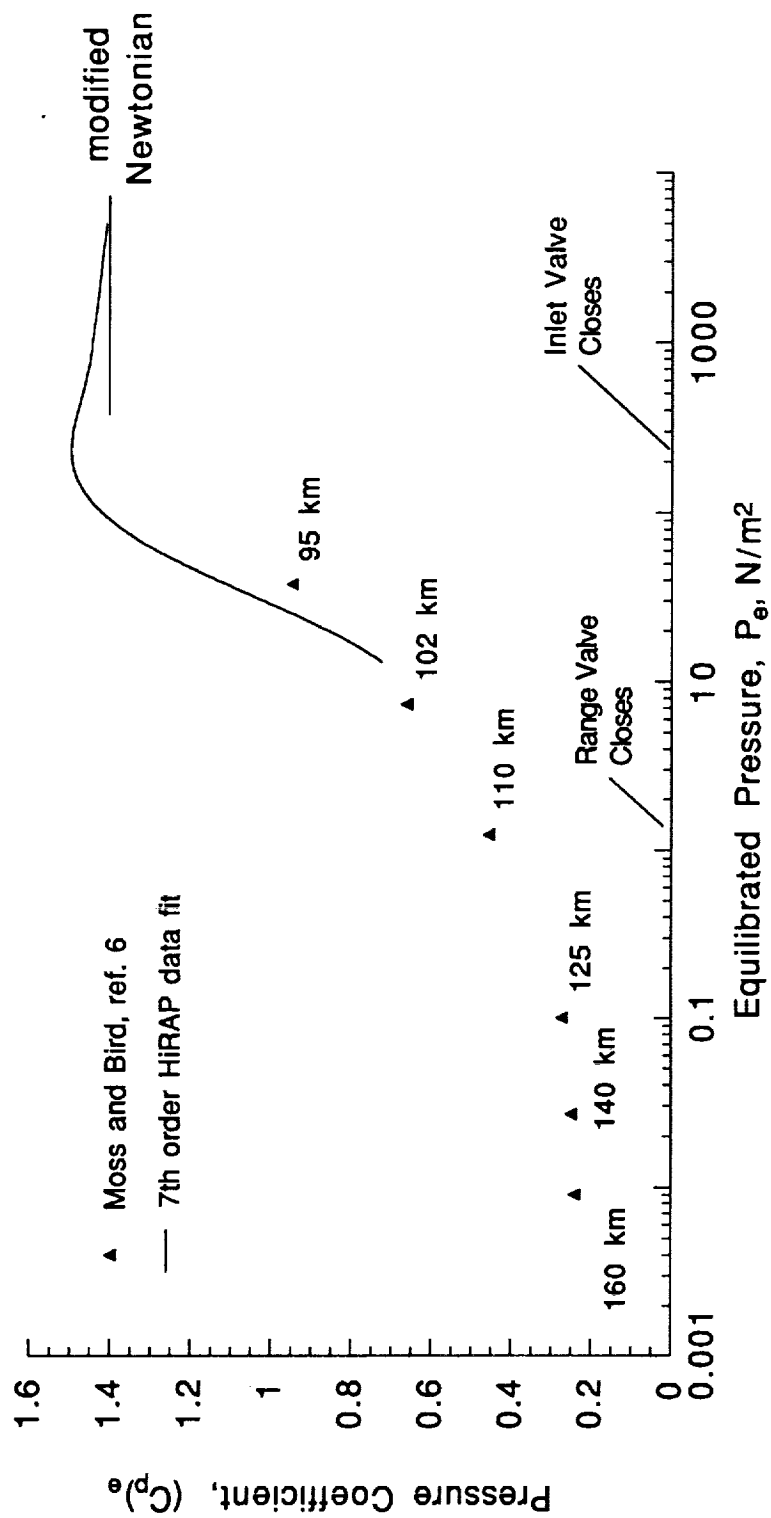


Fig. 8. SUMS orifice pressure coefficient as a function of equilibrated pressure.

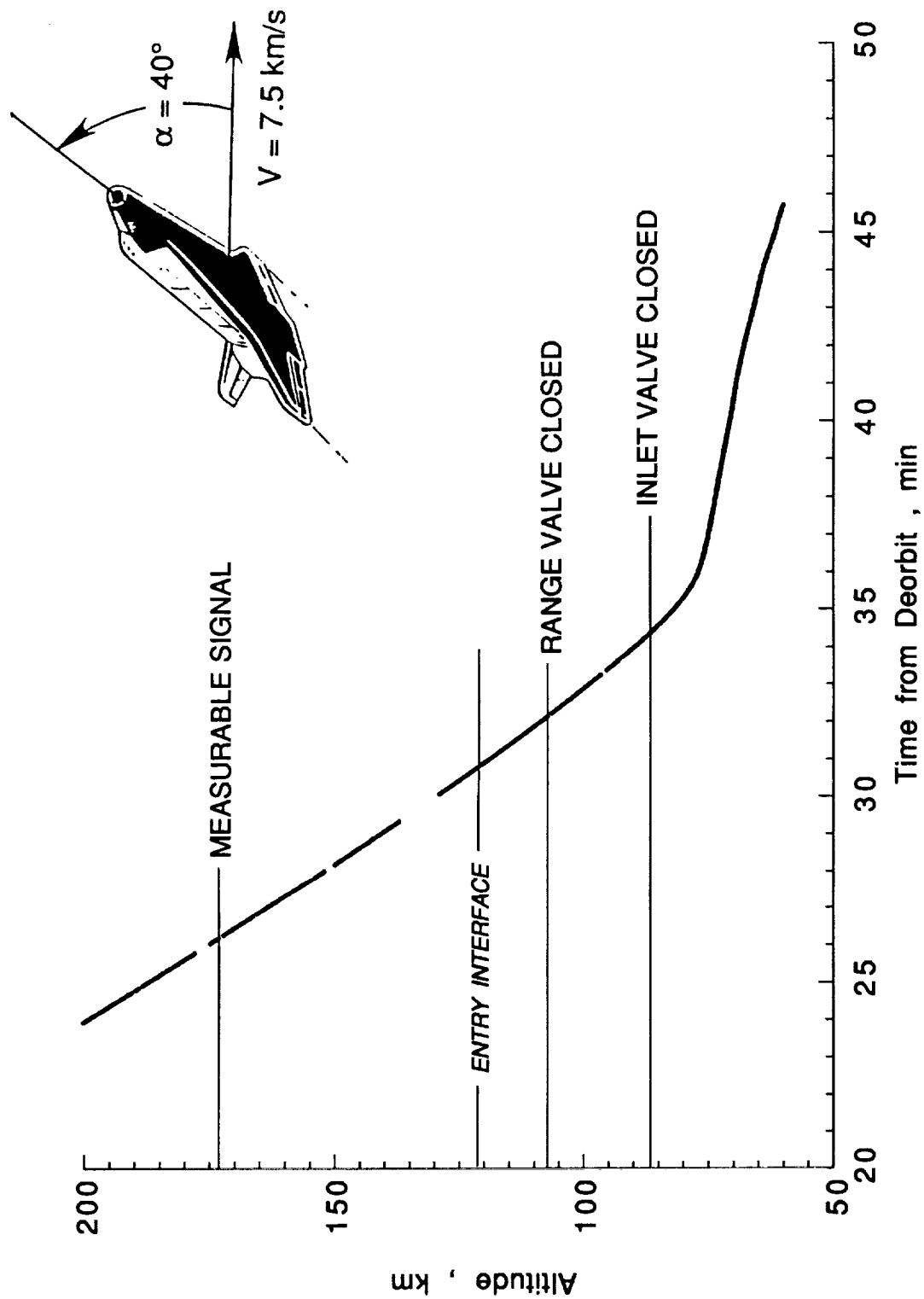


Fig. 9. SUMS altitude measurement domain during STS-35 reentry.

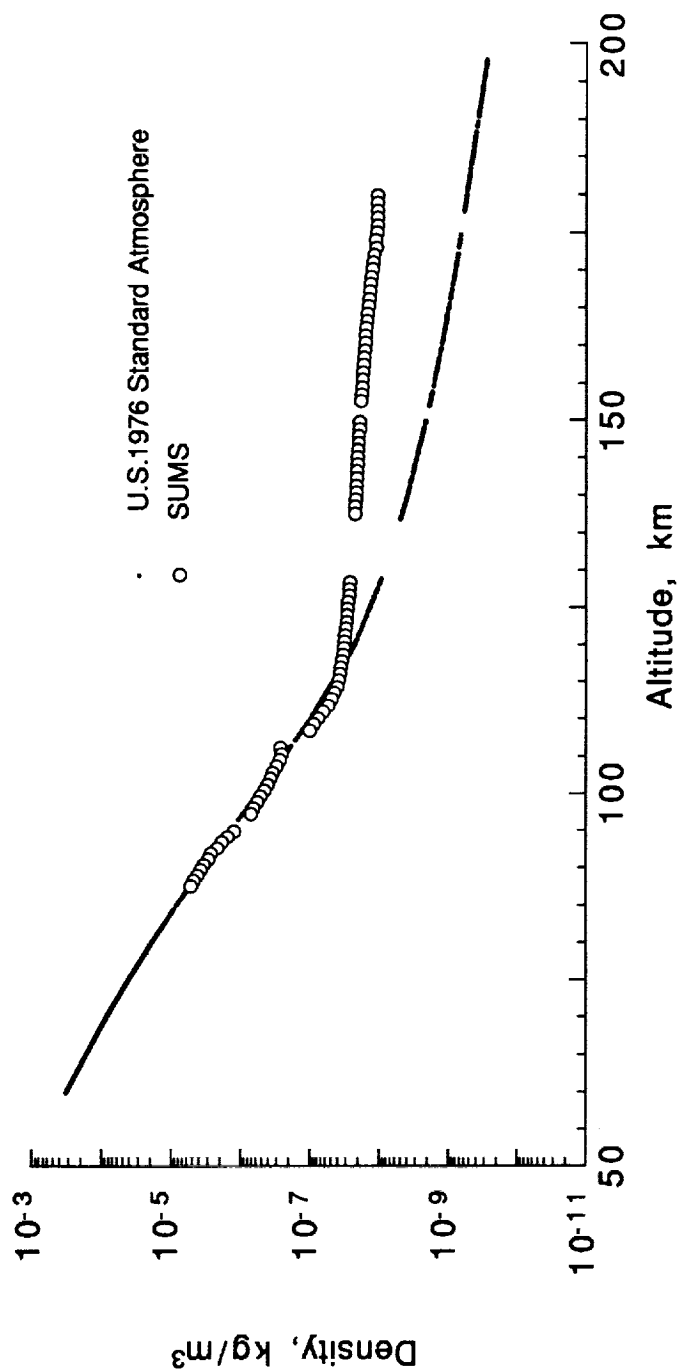
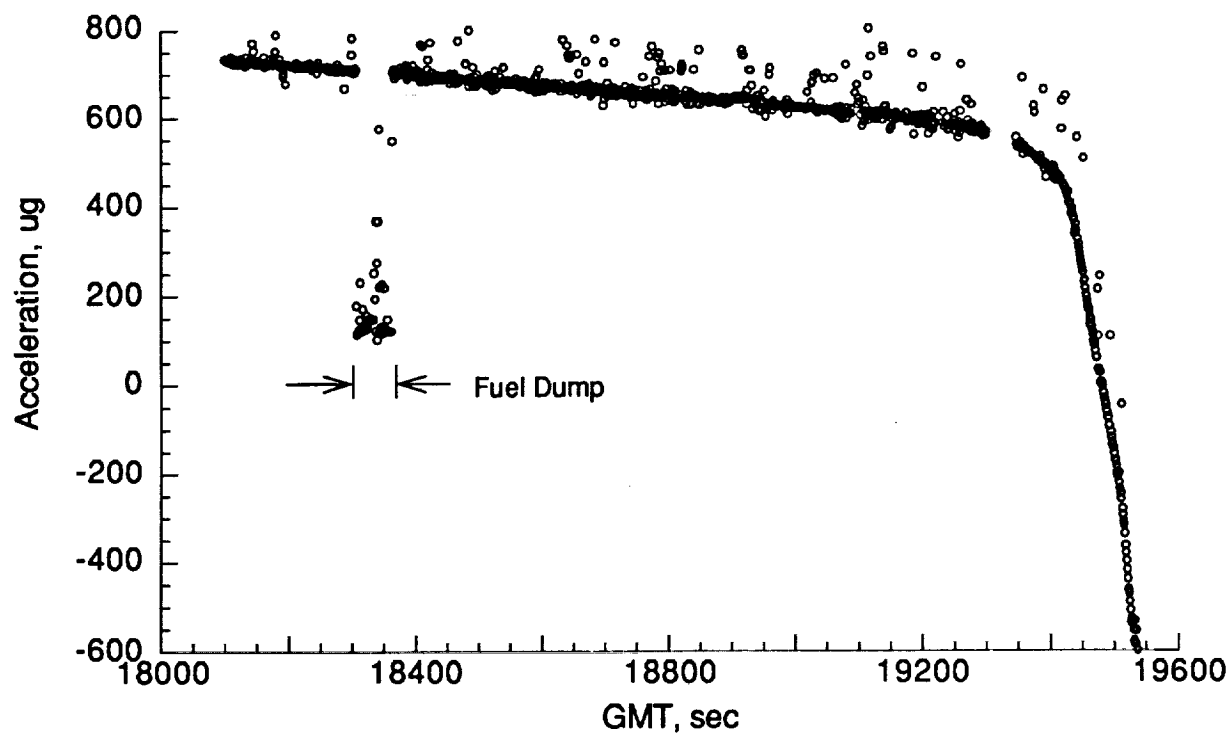
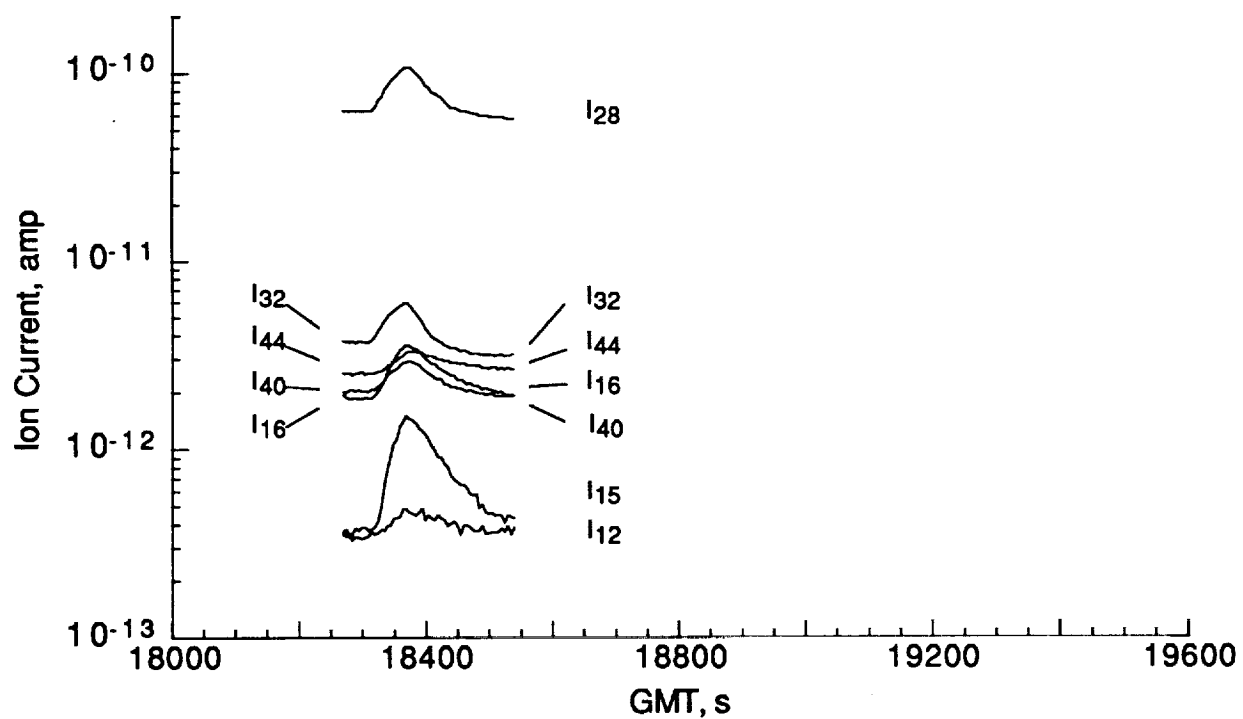


Fig. 10. Comparison of the SUMS measured atmospheric density to the U.S. 1976 Standard atmosphere model.



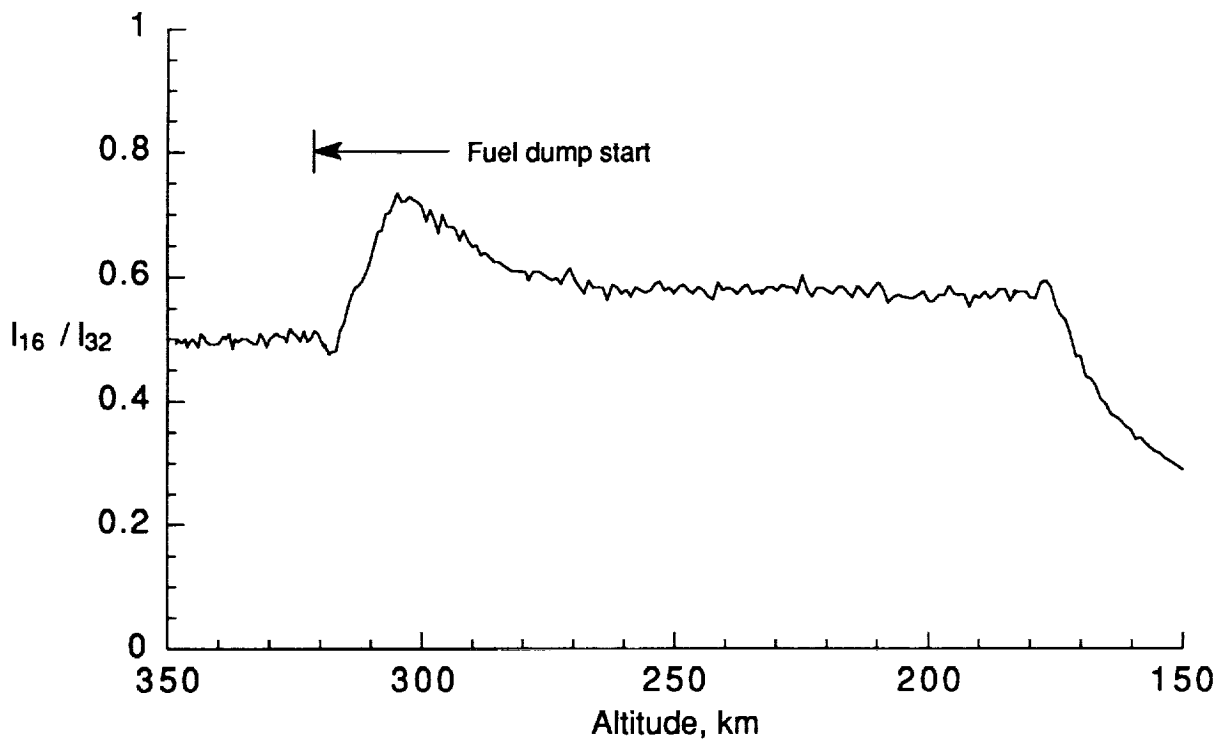


(a) HiRAP x-axis accelerometer data

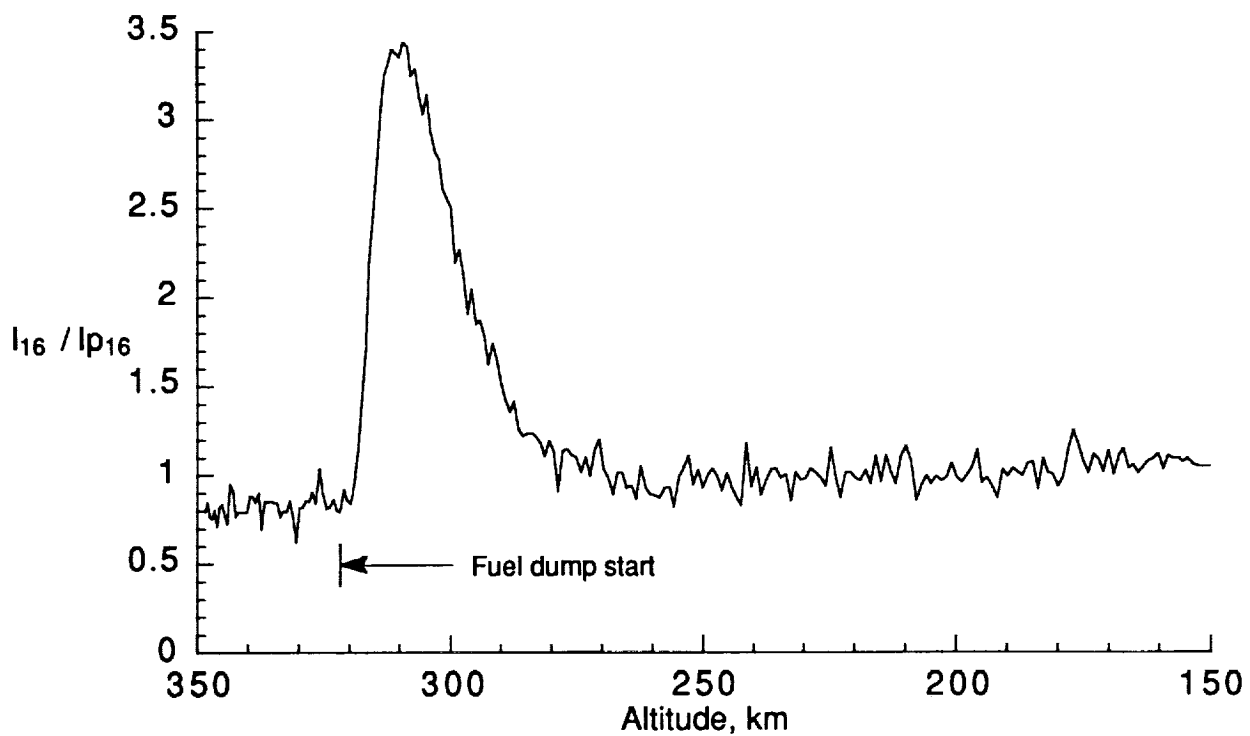


(b) SUMS ion current data

Fig. 11. Comparison of fuel dump induced spectra data.



(a) Ratio of measured 16 to 32 ion current



(b) Ratio of measured to predicted 16 ion current

Fig. 12. Ratios of ion currents of peak 16

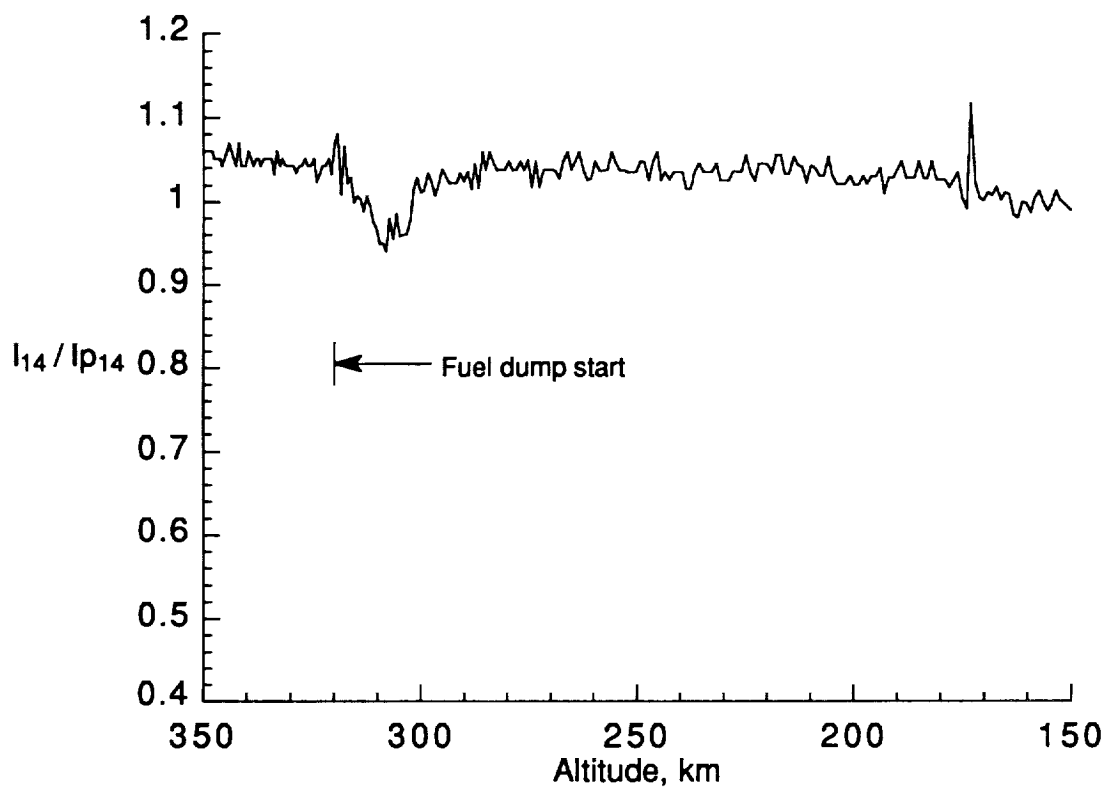
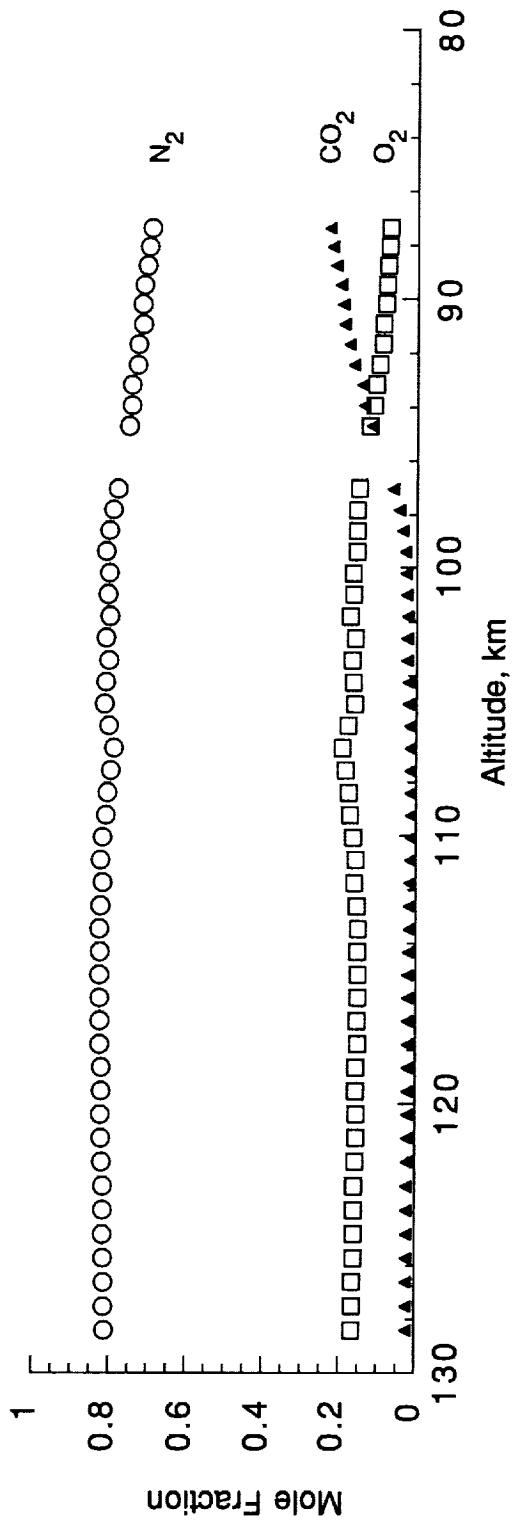
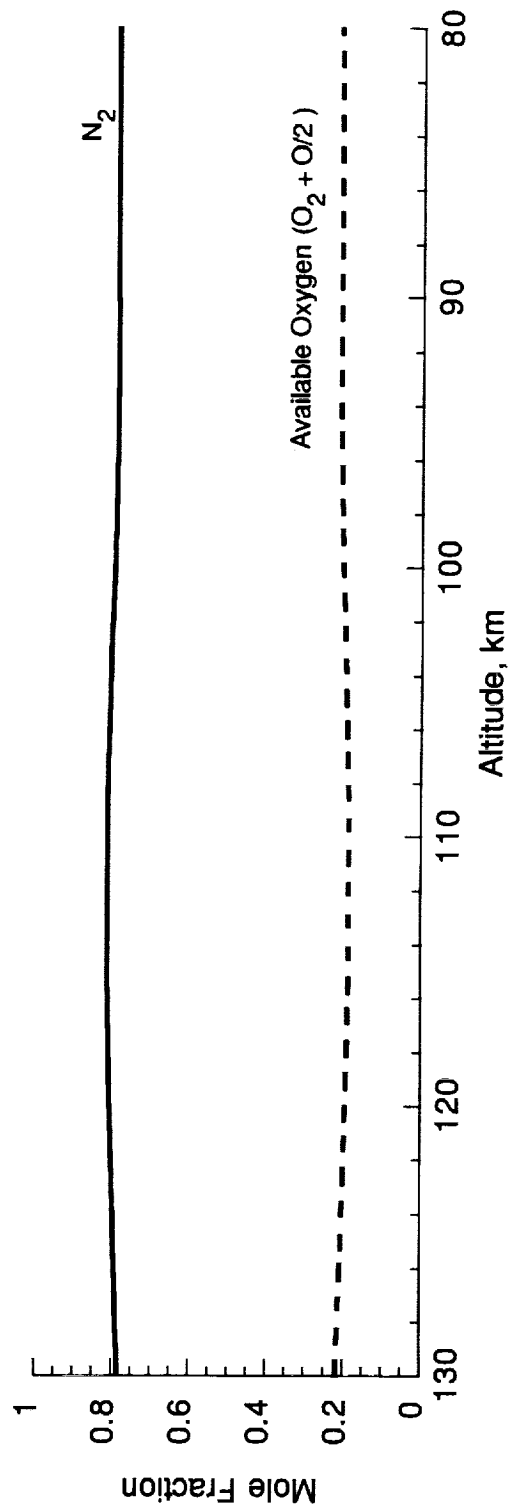


Fig. 13. Ratio of the measured to the predicted 14 peak ion current.



(a) SUMS measurements



(b) 1976 U.S. standard atmosphere model (free-stream)

Fig. 14. Comparison of the SUMS measurements to the 1976 U.S. standard atmosphere model.

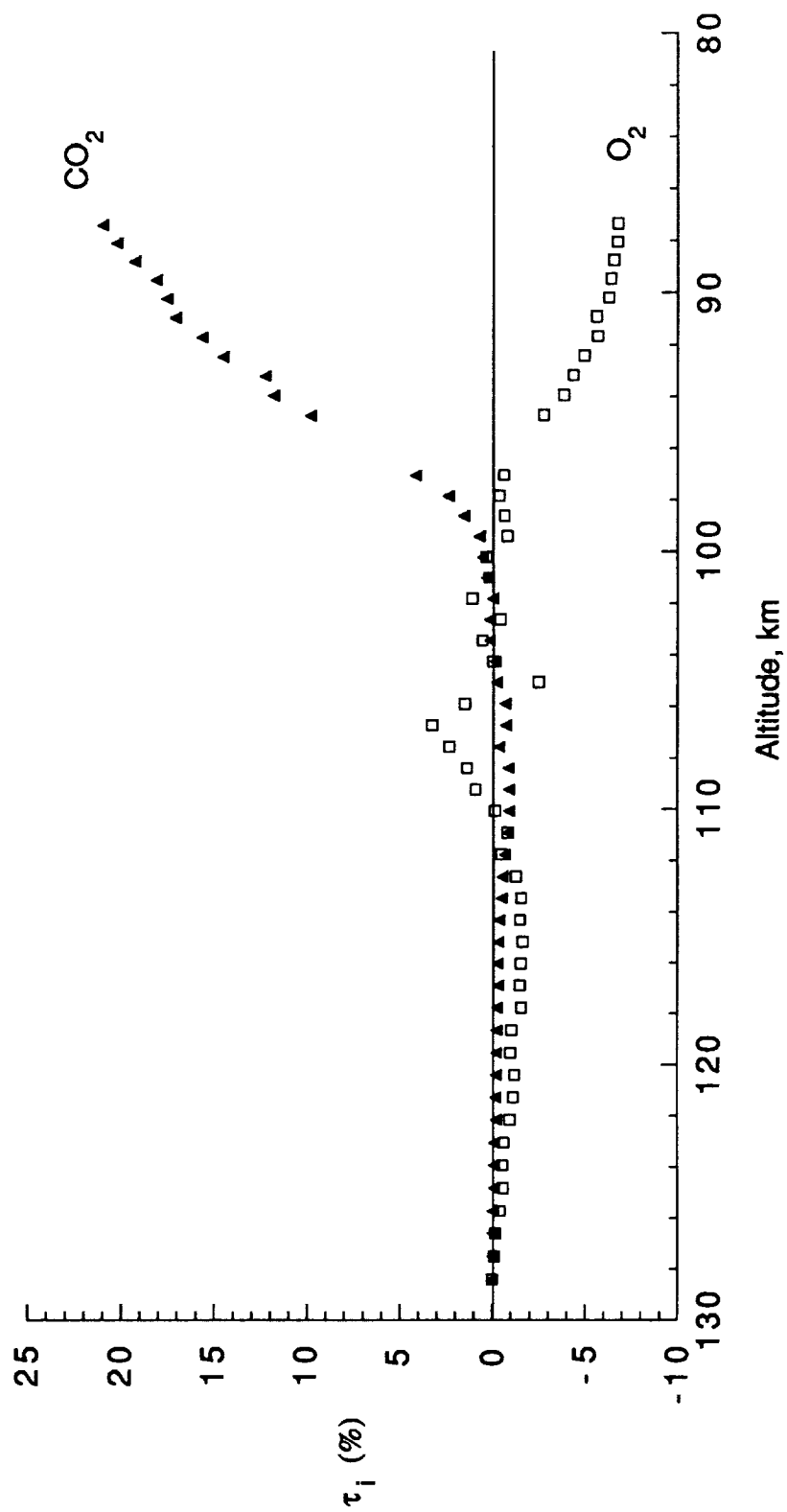


Fig. 15. Change in pressure due to chemistry associated with initial aerodynamic heating during STS-35 reentry.

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13. ABSTRACT (Maximum 200 words) Calibrated pressure measurements for species with mass to charge ratios up to 50 amu/e <sup>-</sup> were obtained from the Shuttle Upper Atmosphere Mass Spectrometer (SUMS) experiment during reentry on the STS-35 mission. Data were collected from 180 km, when the signal rose above the background, to about 87 km, when the SUMS system automatically closed the gas inlet valve. However, data above 115 km was contaminated from a source of gas emanating from pressure transducers connected in parallel to the mass spectrometer. At lower altitudes, the pressure transducer data is compared with the mass spectrometer total pressure with excellent agreement. The free-stream density in the rarefied flow flight regime is calculated using an orifice pressure coefficient model based upon direct simulation Monte Carlo results. This density, when compared with the 1976 U.S. standard atmosphere model, exhibits the wave-like nature seen on previous flight using accelerometry. In addition, selected spectra are presented at higher altitudes (320 km) showing the effects of the ingestion of gases from a forward fuselage fuel dump. An analysis of the spectra data from this event is presented to show that no significant permanent changes occurred which affected the data interpretation at lower altitudes. Further, the localized chemistry from the individual species during the onset of aerodynamic heating is examined to the extent possible for a closed source system, such as SUMS. Near the orifice entrance, a significant amount of CO <sub>2</sub> was generated from chemical reactions with the carbon panels of the Orbiter and absorbed oxygen on the system tubing.				
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